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LOGISTICS SIMULATIONS METAMODEL FOR F404-GE-400 ENGINE MAINTENANCE

by

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13. ABSTRACT (maximum 200 words)

This thesis presents a simulation metamodel that is used to determine initial rotable pool inventories for F404-GE-400 engine modules onboard a deployed aircraft carrier. Millions of dollars can be saved annually by following the metamodel recommendations for changes and reductions in inventories, while at the same time maximizing F/A-18 squadron operational availability. Managers and leaders in the naval aviation and supply communities should use the metamodel as a tool to modify F404 engine module inventory allowance requirements. The metamodel is valid and provides a real means to address the problem of optimizing module inventory levels with operational availability that before would have been overwhelming and impossible to tackle fully. With the power of today's personal computers, combined with sophisticated simulation programs, simulating the F404 engine module repair process at the afloat Aviation Intermediate Maintenance Depot (AIMD) level is accomplishable. The simulation model is developed from real maintenance and usage data and provides a detailed and accurate representation of the repair process. The results of this thesis can be generalized and applied to a wide family of weapon systems. As military leaders struggle more and more with balancing readiness and limited funds, the metamodel presented in this thesis offers a visible decision-support tool.

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LOGISTICS SIMULATIONS METAMODEL FOR F404-GE-400 ENGINE MAINTENANCE

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This thesis presents a simulation metamodel that is used to determine initial rotable pool inventories for F404-GE-400 engine modules onboard a deployed aircraft carrier. Millions of dollars can be saved annually by following the metamodel recommendations for changes and reductions in inventories, while at the same time maximizing F/A-18 squadron operational availability. Managers and leaders in the naval aviation and supply communities should use the metamodel as a tool to modify F404 engine module inventory allowance requirements. The metamodel is valid and provides a real means to address the problem of optimizing module inventory levels with operational availability that before would have been overwhelming and impossible to tackle fully. With the power of today's personal computers, combined with sophisticated simulation programs, simulating the F404 engine module repair process at the afloat Aviation Intermediate Maintenance Depot (AIMD) level is accomplishable. The simulation model is developed from real maintenance and usage data and provides a detailed and accurate representation of the repair process. The results of this thesis can be generalized and applied to a wide family of weapon systems. As military leaders struggle more and more with balancing readiness and limited funds, the metamodel presented in this thesis offers a visible decision-support tool.

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I. INTRODUCTION

A. BACKGROUND

For many years since the end of World War II, the ability of United States naval aircraft carriers to complete their missions has rested primarily on the shoulders of their air wings. Specifically, it has rested on the readiness of the aircraft itself, and the crews who fly and maintain them. It is certain that this reliance will continue into the future with the increasing need for power projection and global presence. The reliability of the aircraft in those air wings is paramount to the continued success of this mission. The cornerstone of Naval Aviation Tactical Air Command (TACAIR), the aviation squadrons at sea onboard aircraft carriers, and the U.S. Marine Corps' attack squadrons is the McDonnell Douglas F/A-18 Hornet multipurpose attack and strike aircraft [Ref. 1]. Even after the new Joint Strike Fighter (JSF) joins the fleet in approximately ten years from now, the F/A-18 will remain in service and play an essential role in naval and marine corps aviation by continuing to be a premier platform in use by the Department of Defense (DoD).

Since 1980, when the first production F/A-18s were delivered to the U.S. Marine Corps, and later that year to the Navy, over 1,000 F/A-18s have been delivered to the United States military services [Ref. 2]. F/A-18s are operating in 37 tactical squadrons from air stations and 10 aircraft carriers worldwide [Ref. 3]. At a cost of $24 million per plane (F/A-18C) ($35million for F/A-18E and F/A-18F), the Department of Defense has

invested over $27 billion in this weapons platform and is committed to maximizing the utility of these aircraft, and ensuring they are safe, reliable and operational as much as possible [Ref. 4].

Two General Electric F404-GE-400 turbofan engines, at a cost of $1.87 million each, power the almost 700 F/A-18As, F/A-18Bs and F/A-18Cs in the service of the Navy and Marine Corps [Ref. 5]. The services rely heavily on the reliable operation of these engines, but have been disappointed with lower than expected performance. With an early history of substandard performance, General Electric (GE) lowered the F404 engine's actual performance required, estimated life and reliability ratings of certain components [Ref. 6].

The original sparing levels of modular components were set based upon GE's original life estimates. Due to the unexpected high failure rate and consequently high repair requirements, a high consumption rate of spare modules consumed all spares inventories quickly. The resulting shortages caused significant degradation of squadron A_O due to inoperable aircraft awaiting engine repairs that were held up by lack of repair modules and repair parts. The F404 engine reliability problems demonstrate how an adverse change in reliability creates added strain on the logistics support system of a major weapon system, like the F/A-18 Hornet.

The failure of the F404 engine to perform at expected levels of reliability has caused inadequate funding for additional repair parts and spare modules. The resultant

asymmetry of failure rates, spare modules and funding is the main problem area for the F404 engine.

B. OBJECTIVE

The purpose of this thesis is to develop a logistics metamodel to predict spares provisioning from mathematical relationships that represent system reliability as a result of simulated repair and maintenance of naval aircraft engines at the organizational, intermediate and depot levels. Squadron readiness is expressed as Operational Availability (A_O) of the F/A-18 Squadron, which is partially determined by the F404 engine and module failure rates and their repair cycle times.

This thesis shows how a method for projecting spares level setting for F404 engine modules can be developed from data generated with a simulation model of the maintenance, or repair cycle. The model uses actual maintenance and usage data. Output data is statistically analyzed and a mathematical formula, or *metamodel*, is defined that represents the relationships between the logistical parameters in the model. The parameters, defined in detail in Chapter III, include repair times, number of modules and engines available as spares and other parameters that affect the repair cycle times of the F404 engine modules. Ultimately, the metamodel may be used in determining sparing levels of the F404 engine modules, while taking into consideration funding constraints and desired A_O.

C. METHODOLOGY

The methodology is to develop a metamodel. A metamodel is a model developed as the result of a simulation. In this case, the A_O data is from the simulation of the repair cycle of the F404-GE-400 engine at the afloat Aviation Intermediate Maintenance Depot (AIMD) level. The metamodel is an equation set equal to A_O, with parameters that represent the important or significant input factors in the repair cycle. Some examples are Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) [Ref. 7:p. 39]. The parameters will most likely have coefficients that are derived from the statistical analysis of the simulation results, or A_O data. Statistical analysis also determines which parameters are significant and therefore included in the metamodel [Ref. 8].

The simulation of the repair cycle of the F404 engine is accomplished with the commercial computer software product Arena. The simulation model used in this thesis is based upon the original work of Kang, who constructed a model that provides basic simulation of the repair cycle of engines in an F/A-18 aircraft squadron at the organizational, intermediate, and depot levels [Ref. 9]. Kang's model, written in Arena, outputs A_O of the squadron as it simulated failures of engines over a user-defined time period.

A truly representative simulation model is essential to developing a valid and accurate metamodel. A major portion of this thesis is dedicated to the collection of actual maintenance data of the F404 engine and applying it to a modified simulation model that accurately reflects the repair cycle and its parameters.

D. RESEARCH QUESTIONS

When considering sparing levels of the F404 engine modules, the following is a list of primary research questions that are addressed by this thesis:

- What are the critical factors for aviation readiness?
- What are the relationships between these factors and readiness?
- What are the relationships between these factors and cost?
- How can a logistics metamodel help decision-makers at the organizational, intermediate, and depot levels?

E. ORGANIZATION

Chapter II provides background of the Naval Aviation maintenance program. It discusses the critical factors and A_O with regard to support of readiness, provides a description of the F404 engine and its modules, as well as an overview of the rotable pool concept are provided. Chapter II ends with a description of the F404 engine repair cycle. Chapter III covers the development of the simulation model. The metamodel development, Arena software, and simulation assumptions and parameters are discussed. With the complete model from Chapter III, Chapter IV discusses running the simulation model, its output, and the development of the metamodel from the output. Conclusions and recommendations are provided in Chapter V.

II. BACKGROUND

A. THE NAVAL AVIATION MAINTENANCE PROGRAM

Determining the levels of maintenance during development of a system's life cycle is an important step in defining that system's maintenance concept, and hence ultimately its future reliability [Ref. 7:p. 27]. Early in the development of the F/A-18 program, a three-echelon maintenance system structure was defined for the F404 engine [Ref. 7:p. 115]. The first echelon, or *organizational* level, performs limited repair that requires basic technical skills. Significant repair equipment at this level is that necessary to remove and install an engine. The operational component that makes up the first level is the aircraft Squadron. The second echelon, or *intermediate* level, performs extensive preventative and corrective maintenance requiring elaborate technical skills and repair facilities. This level is called the Aviation Intermediate Maintenance Depot (AIMD) and they exist as shore facilities located at air stations, as well as onboard deployed aircraft carriers as detachments from the shore facilities. At the third echelon, or *depot* level, the most technical, complex and costly repairs are performed. For the F404 engine, there is only one depot at this level, which is Naval Aviation Depot at Jacksonville, Florida. For the F404 engine, the level of repair accomplishable at the intermediate level is almost as extensive as that at the depot level. Means to measure the effectiveness of this three-echelon system are discussed next.

B. CRITICAL FACTORS IN NAVAL AVIATION MAINTENANCE

The Naval Aviation and the Naval Supply Corps communities have clearly defined measures of logistics and the success of their logistics efforts. Stepping back from their approaches, this thesis takes a more academic and basic look at the important or critical factors of logistics support. Blanchard lists eleven factors that are measures of logistics: reliability, maintainability, supply support, test and support equipment, organizational, facility, transportation and handling, software, availability, economic, and effectiveness [Ref. 7:p. 27]. Narrowing the scope to factors that affect the A_O of an F/A-18 Squadron in relation to the F404 engine modules, the simulation model developed in this thesis addresses reliability, maintainability, and supply support factors.

Reliability is defined as the probability that a system will perform for a given period of time [Ref. 7:p. 27]. The failure rates of the F404 engine and its modules represent their reliabilities and are used to determine the simulated inflow of engines to repair and of which modules to simulate repair.

The maintainability factor includes corrective and preventive maintenance times expressed in man-hours [Ref. 7:p. 37]. The process times for repairing the F404 engine and engine modules comprise significant data and are utilized in the simulation model. Times for preventive maintenance of the F404 modules are included in the model to represent one aspect of the module repair cycle because preventative maintenance time does minimally affect on the total repair time and total A_O. Generally, preventative maintenance times are less than repair times and therefore do not cause a bottleneck in the

repair cycle. Also, preventative maintenance is usually scheduled in advance so as not to interfere with critical corrective maintenance.

The supply support factors that are important, including that of the F404 engine, to any logistics pipeline are (1) probability of a system remaining operational with spares availability considerations, (2) probability of mission completion, (3) spare part quantity determination, and (4) inventory considerations. These factors are especially relevant when considering the modular design of the F404 engine and the practice of modular sparing as is used with this engine. The metamodel developed in this thesis will provide alternative ways of determining inventory levels. But before describing this in more detail, a background of the F404 engine is provided first.

C. F404-GE-400 ENGINE

1. Background

This thesis simulates the repair process of the General Electric F404-GE-400 turbofan engine due to its large application in the navy's fleet of F/A-18 Hornet strike fighter aircraft. Additionally, complete usage, maintenance, and repair data on the F404 engine exists since the first full-scale development F/A-18s were delivered to the Navy in 1979 [Ref. 2]. With over 3,600 engines delivered worldwide, the track history of the F404 engine is well documented [Ref. 10].

The F404-GE-400 engine is installed in all F/A-18As, F/A-18Bs and most F/A-18Cs, almost 700 aircraft. During production of the F/A-18C, the first F404-GE-402 EPE (Enhanced Performance Engine) engine, with an 11% improvement in thrust, was

delivered by General Electric and became the engine for all subsequent F/A-18Cs, as well as all F/A-18D, F/A-18Es and F/A-18Fs. See Table II.1 for summary engine specifications of the F404-GE-400 and 402 engine [Ref. 11].

Feature	F404-GE-400	F404-GE-402
Maximum Length (in.)	159	159
Maximum Diameter (in.)	34.5	34.5
Maximum Weight (lbs.)	2180	2282
Bypass Ratio	0.34	0.27
Maximum Thrust (lbs.)	16,012	17,775
Engine Compression Ratio	25:1	27:1
Fan Pressure Ratio	3.9	4.3
Compressor Pressure Ratio	6.3	6.23
Thrust to Weight Ratio	7.1	8.1

Table II.1. F404-GE-400 Engine General Specifications.

2. Modules

Designed with easier maintenance in mind, the F404 engine consists of six main modules. This modularity is one of the essential aspects of its design, which by design facilitates easier and quicker repair of any component. This design also allows for easy exchange of modules from other engines or from stock of repair parts. Older engine designs typically did not employ a modular concept, and hence require more maintenance man-hours for breaking down, repairing, and reassembling engines. The modularity feature of the F404 has proven to be convenient, especially considering the significant amount of maintenance required by the engine.

With modular design, the F404 engine also provides the opportunity to track failure and maintenance statistics by module, thus allowing more detailed planning of maintenance and spare parts requirements. The six modules that comprise the F404 engine, and MTBF rates for the period February 1997 through July 1998, are shown in Table II.2 [Ref. 12]. The detailed degree to which data collection is possible with modular design and repair is demonstrated by the availability of modular MTBF data. The availability of this data makes such analysis as this thesis possible.

The failure rate is another way of expressing the reliability of a component. Mathematically, it is the reciprocal of the MTBF. The engine MTBF, as listed in Table II.2, is much less than the individual module MTBF's because the failure of any module, or multiple modules, can cause the failure of the an engine as a whole unit. The engine's failure rate then, expressed as the reciprocal of the MTBF, is greater than the module's failure rates. The next section describes the module spare concept called "rotable pool," which takes advantage of the F404 modularity design.

Engine	**Module**	**MTBF (hours)**
F404-GE-400		**383.5**
	Fan	679.6
	High Pressure Compressor	769.3
	Combustor	696.3
	High Pressure Turbine	692.3
	Low Pressure Turbine	641.3
	Afterburner	515.5

Table II.2. F404-GE-400 Engine and Module Mean Time Between Failures (MTBF).

D. ROTABLE POOL

1. Concept and Operational Availability

A primary reason for designing the F404 engine to be constructed of modules was to take advantage of rotable pools to minimize aircraft down time. A rotable pool is a stockpile of spare parts (in this case an engine module), that provides a spare to facilitate a quick repair of a broken engine. This allows the engine to be repaired and reinstalled in the aircraft quickly and without waiting for the actual broken part to be repaired. The broken module is repaired later at a scheduled rate to maximize the productivity and efficiency of the maintenance facility. After repair, the module is returned to the pool stock and awaits issue for the next broken engine.

The net result of this type of repair process is a *reduction in repair cycle time*, and ultimately, a higher aircraft A_O is achieved. This is expressed as

$$A_o = \frac{MTBM}{MTBM + MDT},$$

where *MTBM* is the mean time between maintenance and *MDT* is the maintenance down time [Ref. 7:p. 70]. Described relationally, as *MDT* becomes less, *MTBM* + *MDT* becomes less, and A_O becomes greater (the smaller the denominator, the larger the quotient).

2. Problem

The objective of improving A_O by using a rotable pool can only be achieved when the spare stock level is one or more. When the pool runs out of spares, then the down

time becomes a function of engine or module repair time vice time to swap a module and reinstall the engine. This dramatically increases down time of the engine, and hence aircraft as well.

A proper spares inventory level minimizes risk of running out of spares. Not withstanding, the benefit of valid funding requirements projections, this alone justifies the necessity of an accurate inventory level metamodel. To complete the background chapter, the next and last section provides an overview of the actual repair cycle of the F404 engine. After that section, Chapter III describes the development of the metamodel itself.

E. F404-GE-400 ENGINE REPAIR CYCLE

The repair cycle of the F404 engine and its modules through the F404 maintenance system is depicted in Figure 2.1. This figure represents all three levels of repair: organizational, intermediate, and depot. The afloat intermediate level, or Afloat Aviation Intermediate Maintenance Depot (AIMD), is similar in function to the Shore AIMD intermediate level of maintenance (Shore AIMD), but operates separately onboard aircraft carriers during deployments. Since this thesis focuses on the repair cycle while at sea, or during deployment, the ashore aspect of the AIMD repair process is not simulated. However, to make the model as realistic as possible and to represent to fact that engines and modules are repaired elsewhere than the Afloat AIMD, the model does simulate the time to receive a replacement unit from either the Shore AIMD, or the Depot.

Figure 2.1 shows the flow of a broken engine through a basic repair decision process. The first diamond asks the question whether repair can be completed at the squadron level. If not, then the engine is sent to the Afloat AIMD, and if it can, then the engine is repaired and the aircraft is operational. The ability to repair question is asked again in the second diamond flow chart symbol at the Afloat AIMD level. Engines

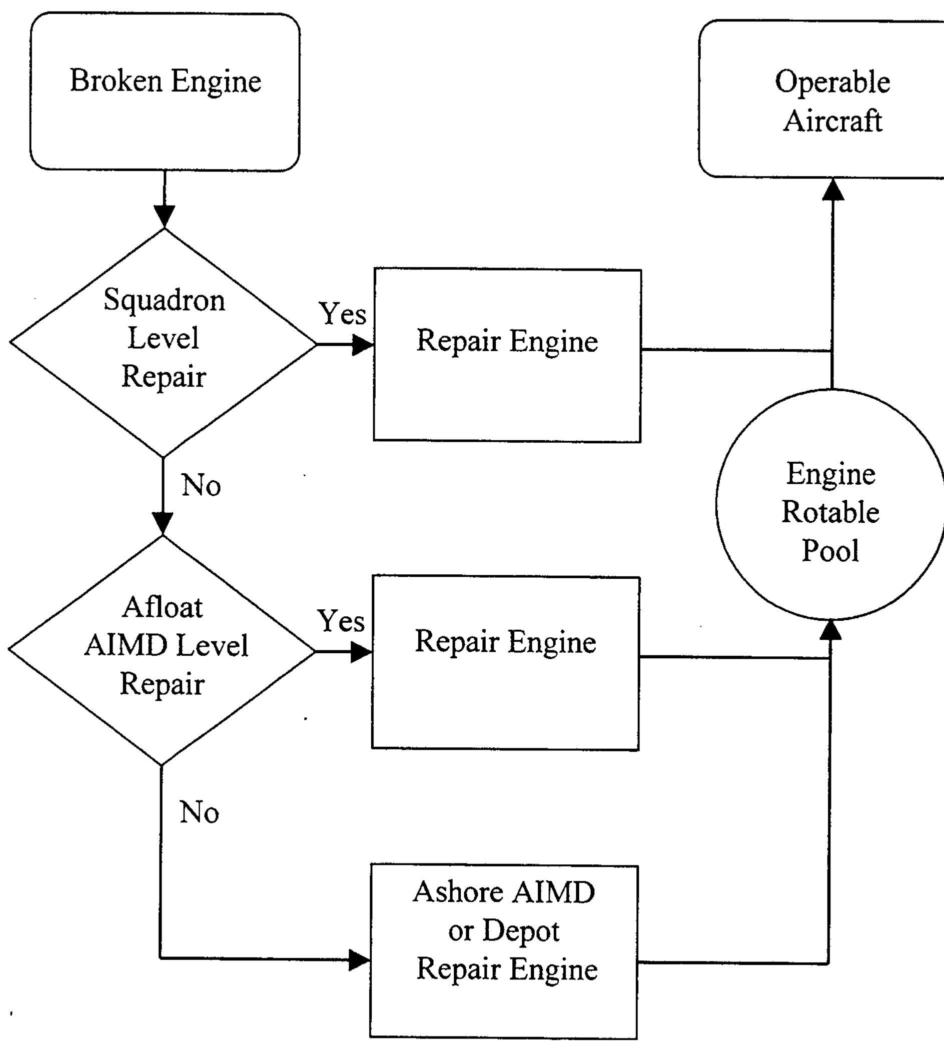


Figure 2.1. F404-GE-400 Engine Repair Cycle – Overview.

repaired at this level are sent to a rotable pool while awaiting installation in an aircraft. Engines not repairable at the Afloat AIMD level are sent to Ashore AIMD or to a Depot, where they are repaired and returned to the rotable pool onboard the aircraft carrier.

A more detailed flow of the squadron level repair cycle is shown in Figure 2.2. Squadrons first troubleshoot an engine and determine if repair is possible at that level. If

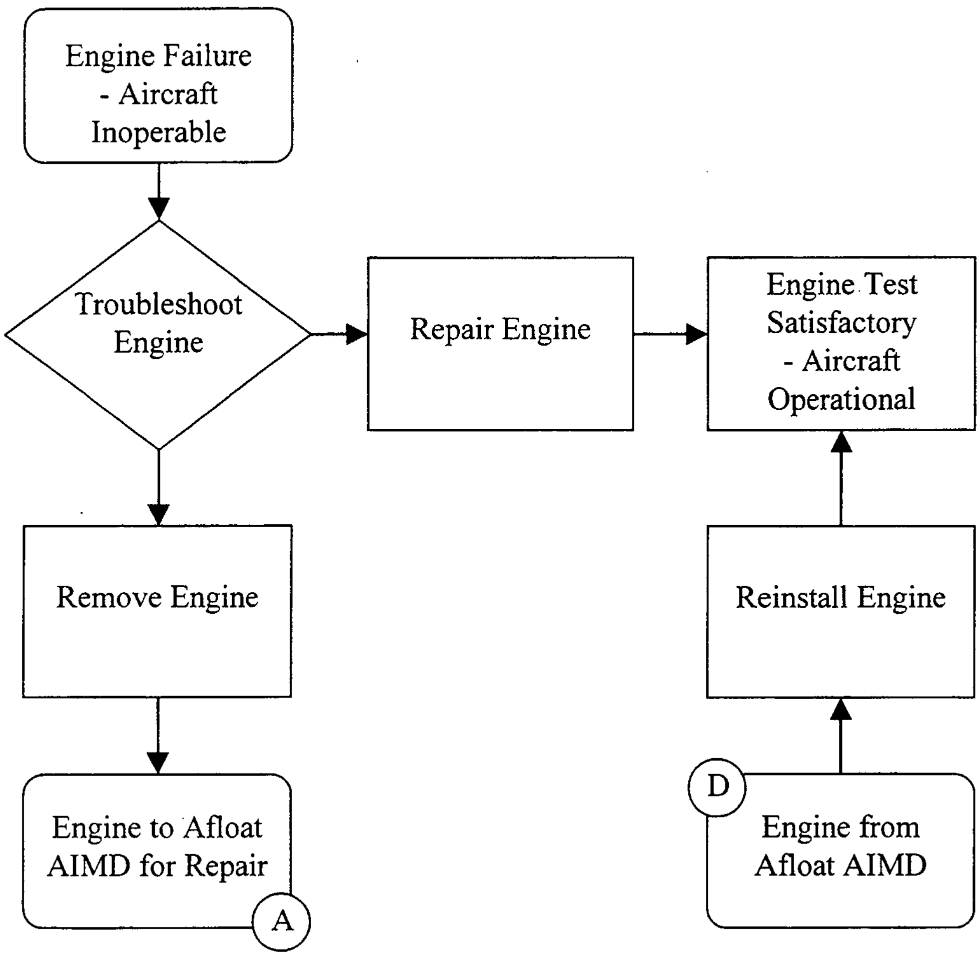


Figure 2.2. F404-GE-400 Engine Repair Cycle – Organizational Level.

so, as is rarely the case, repair is accomplished, usually with the engine still in the aircraft. If not, then the squadron removes the engine and passes it to the Afloat AIMD, as annotated with connector “A.” The squadron is also responsible for reinstalling engines and conducting operational testing of the engines in the aircraft.

Figure 2.3 shows the details of engine and module repair at the Afloat AIMD level. Inoperable engines are received from the organizational, or squadron, level as annotated with connector “A.” A Maintenance Engineering Inspection (MEI) determines if the Afloat AIMD has the capability to repair the engine faults. If not, then the engine is sent to an ashore repair facility. If the engine can be repaired as a whole unit, it is and then sent to the engine rotable pool. If necessary, as is most of the time, the engine must be disassembled into its modules for modular repair.

There are four options for modular repair at the Afloat AIMD level shown in Figure 2.3. Once the module is disassembled from the engine, more extensive damage may be found that was not revealed during the MEI. Under these occasional circumstances, the module is sent ashore for repair, as represented by connector “B.” Also, modules that were not originally designated as needing repair by the MEI may be found in need of repair and are subsequently repaired. Many modules require scheduled preventative maintenance, and the remaining few are placed directly in the module rotable pool to be used in the assembly of an engine. Modules that have been repaired ashore are received aboard the carrier and placed in the module rotable pool, as represented by connector “C.” The Afloat AIMD reassembles engines from module

rotable pool stocks and returns whole engines as needed to the squadron level, as represented by connector "D" in Figure 2.3.

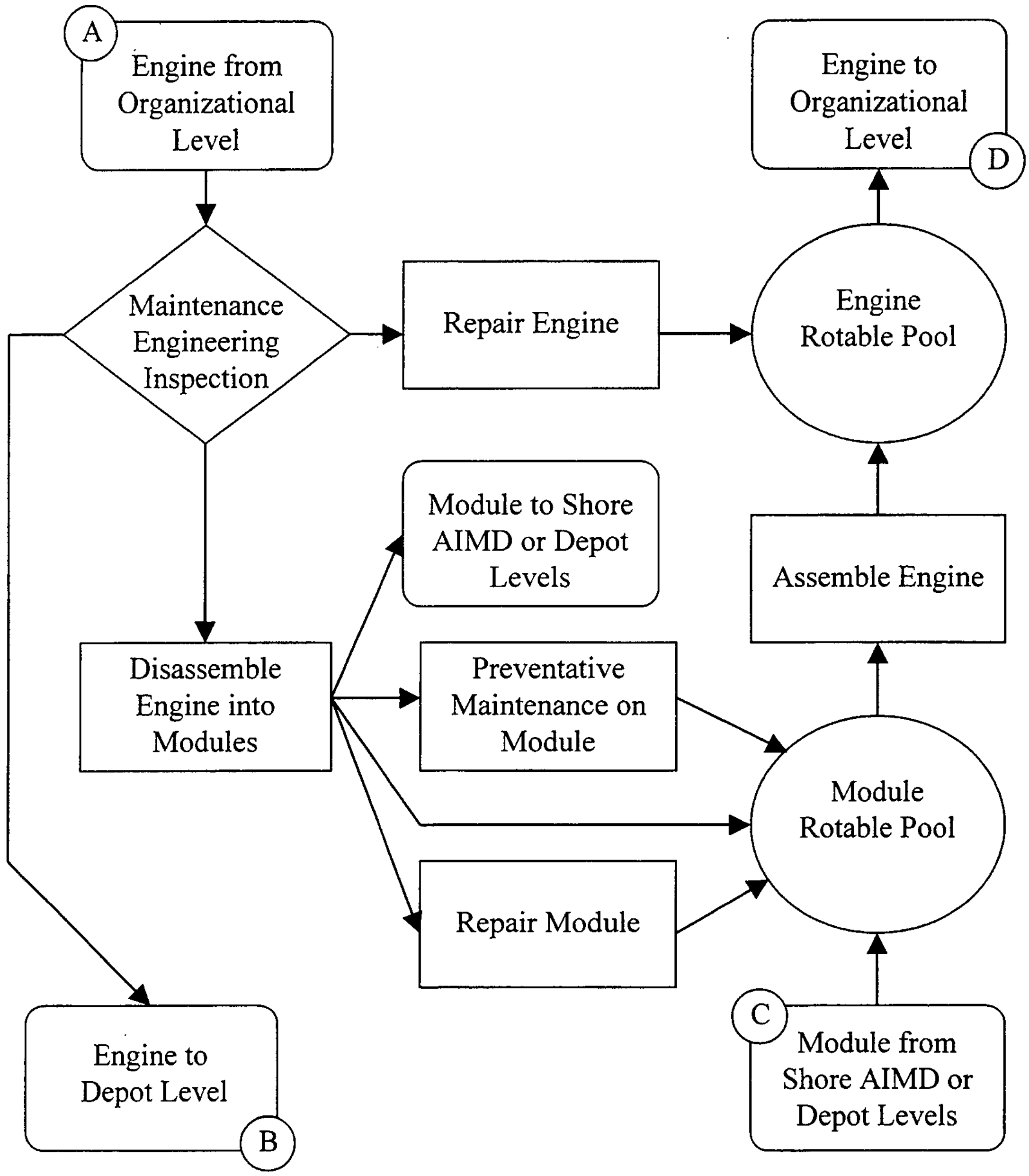


Figure 2.3. F404-GE-400 Engine Repair Cycle – Intermediate Level.

The flow of engines and modules at the Shore AIMDs and Depot levels is similar to that represented in Figure 2.3. However, for purposes of this thesis and the simulation model, their repair cycle flow at these levels is simplified to just show that they can and do go off ship and return. This is represented through connectors "B" and "C" in Figure 2.4.

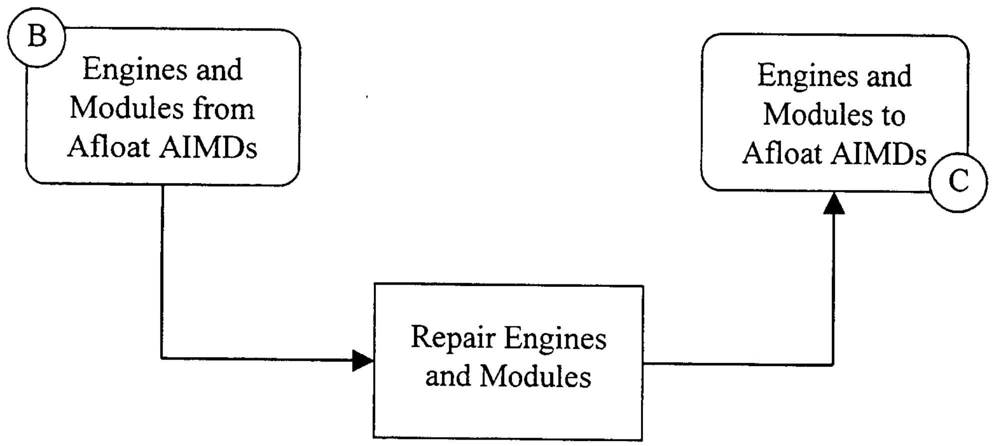


Figure 2.4. F404-GE-400 Engine Repair Cycle – Shore AIMD and Depot Levels.

III. SIMULATION MODEL DEVLOPMENT

A. USING SIMULATIONS TO DEVELOP METAMODELS

The development of metamodels from simulation modeling has been shown effective. For example, by applying regression analysis to output from a simulation model, Madu and Kuei were able to develop a metamodel that minimizes the cost of downtime in a multi echelon closed queuing repairable system [Ref. 8]. Furthermore, as a common method for analyzing simulation model output, regression analysis is a proven technique.

> Regression models are often applied by management scientists to analyze simulation data as well as real-world data. It is well recognized that the data of a simulation experiment can indeed be analyzed through a regression model that serves as a metamodel (see Kleijnen 1987, p. 241). [Ref. 13:p. 1164]

The successful uses of simulation models to develop metamodels, and more importantly to successfully interpret the output into a meaningful and useful form, is more practical and affordable today than ever before. The vast proliferation of ever more capable Personal Computers (PCs) that are more powerful than yesterday's mainframes makes simulation modeling easy for many practitioners. High-speed computer processing power makes this especially so. Software features like random number generators are common place background functions that do not cause any detectable delay in simulation run times. This allows practitioners to program simulations with multiple complex variables. The development of PC based input and output analyzers

also simplify the simulation process. Even common software packages come with complex data analytical tools (i.e., Regression Analysis in Microsoft® Excel) that make previously difficult problems easy to solve.

In several regards, this thesis would not be possible if not for the power of today's PCs and their software. Although the raw data provided by NAVAIR originated from a non-PC system, all of the author's data grooming and analysis was accomplished on a PC. Additionally, the simulation model was developed and run on a PC. Such accessibility to utilizing today's computer's potentials provides endless opportunities for further research and more extensive simulation modeling. An overview and the capabilities of the simulation modeling software utilized in this thesis is provided in the next section.

B. OVERVIEW OF ARENA

The creators of Arena software answer the question "What is Simulation?" with these thoughts.

> *Simulation* refers to a broad collection of methods and applications to mimic the behavior of real systems, usually on a computer with appropriate software. In fact, "simulation" can be an extremely general term since the idea applies across many fields, industries and applications. These days, simulation is more popular and powerful than ever since computers and software are better than ever. [Ref. 14:p. 3]

Arena provides the tools necessary to simulate complex problems. It allows the user to visually model a system in the same manner as it works. In other words, Arena is programmed using icons and connecting lines that represent actual movement of entities

through a system. This graphic approach allows the user to visualize the model as he would visualize the real system. The benefits are that simulation model development takes less time, and a more accurate model can be designed and working in far less time than with conventional computer programming languages.

Because of Arena's ability to mimic real systems so well through the use of many predefined modules, developing a model of the F404 engine repair cycle was not too difficult. After completing the simulation model, it was easy to modify the parameters to facilitate several "what if?" scenarios, as well as complete the simulation runs, as will be discussed later in this chapter. The next section describes the details of how the F404 engine repair cycle is converted into an Arena simulation model.

C. SIMULATION MODEL SCOPE AND ASSUMPTIONS

Focusing on the afloat portion of the F404 engine repair cycle, the model simulates the processes and flow of work as described in Chapter II, and as diagrammed in Figures 2.2, 2.3 and 2.4. Detailed flow of the repair cycle at the shore repair facilities was not included. Due to the interaction of shore activities with multiple afloat activities, in order to render an accurate simulation model, undertaking the simulation of shore activities would require representation of all Afloat AIMDs, and that was considered too large for this thesis.

The following assumptions are made to simplify the simulation model and they do not significantly affect repair cycle time or Squadron A_O.

- F404 engine modules that have already begun the repair process at the Afloat AIMD level and are later discovered to need repair at a higher level (Shore AIMD or Depot) are ignored. These circumstances occur infrequently.

- Although modules are physically owned and stored by Supply S-6 Division on board an aircraft carrier, in this model all Ready-For-Issue (RFI) modules and engines are held logically in rotable pools at the Afloat AIMD level.

- The Afloat AIMD operates 24 hours a day.

- Both engines in a single aircraft do not fail at the same time.

- Fifty percent of modules that are *not* in need of repair do require preventative maintenance. Time assignments for preventative maintenance are based upon the combined corrosion treatment times for the Fan Module at the intermediate level of repair and are distributed using the lognormal distribution. The other 50% are immediately placed in the module rotable pool as RFI. The basis of this assumption stems from and interview with a Power Plants Production Chief Petty Officer who stated that he estimated 60% to 70% of all modules end up with some kind of preventative maintenance [Ref. 15]. Actual maintenance data from the Naval Aviation Logistics Data Analysis (NALDA) System database indicates 15.4% of the modules repaired between February 1997 and July 1998 received corrosion treatment, which is considered a primary form of preventative maintenance and the only one documented in NALDA [Ref. 16]. The Chief also suggested that more preventative maintenance is being performed than is being documented. By "splitting the difference," the author assumes 50% of the modules not going to repair (afloat or ashore) receive preventative maintenance.

- The repair cycle is a closed loop and no engines or modules are condemned or replaced by new stock. This assumption has no affect on the cycle time because the time to ship a condemned unit and receive a replacement from the supply system is approximately equal to the repair time, on average. Also, the occurrence of condemning engines or modules is so rare that it is considered insignificant to the simulation model. For the 18-month period of February 1997 through July 1998, only 9 engines were condemned out of 3,521 that were processed for repair (0.26%) [Ref. 12].

- Initial engine rotable pool inventory is 2 engines. This simulated parameter is static throughout simulation runs. To keep the model as representative of the actual repair cycle as possible, the NAVAIR allowance level of 2 is used for the initial engine rotable pool inventory. Additionally, NAVAIR module

allowances are used as the baseline for all analysis and conclusions as presented in Chapter V. These allowances, as listed in Table III.1, are for a deployed aircraft carrier. [Ref. 16]

Unit	Allowance Quantity
Engine	2
Fan Module	3
High Pressure Compressor Module	2
Combustor Module	2
High Pressure Turbine Module	3
Low Pressure Turbine Module	2
Afterburner	3

Table III.1. F404-GE-400 Engine and Module Initial Inventory Allowances for Deployed Aircraft Carriers. From Ref. 16.

- We do not consider cannibalizations. In other words, this simulation model does not simulate the cannibalization of either the engine or the modules. This assumption may cause Squadron A_O to be less in the simulation model than in real circumstances. However, the number of broken engines and modules does not change, nor does the time to repair them. Therefore, the evaluation of rotable pool spare inventories based upon repair cycle times does not change.

- There are 24 F/A-18 aircraft onboard the simulated carrier. With 2 engines per aircraft, the number of engines in the simulation model is 48.

D. SIMULATION MODEL PARAMETERS

1. System Response

- Operational Availability (A_O). This is the percent of squadron aircraft that are ready to fly at any time.

2. Simulated Determinants

The statistical distributions in parentheses are the values used for setting the insignificant parameters for the simulation runs. The statistical distributions are determined from actual maintenance data (NALDA database), collected during the 18-month period between February 1997 and July 1998, using a data input analyzer tool in Arena [Ref. 17].

- Time to troubleshoot engine at Squadron level (LOGN(3.34, 3.72))[1],
- Time to repair F404 Engine at Squadron level (-0.001 + GAMM(1.73, 1.01))[2],
- Time to remove and replace engine at Squadron level (-0.001 + GAMM(4.01, 1.63)),
- Time to conduct Maintenance Engineering Inspection (MEI) at Afloat AIMD level (EXPO(4.5))[3],
- Time to repair F404 Engine at Afloat AIMD level (-0.001 + LOGN(15, 82.4)),
- Time to remove and replace Fan Module at Afloat AIMD level (LOGN(4.79, 4.6)),
- Time to remove and replace HP Compressor Module at Afloat AIMD level (LOGN(5.42, 5.8)),
- Time to remove and replace Combustor Module at Afloat AIMD level (LOGN(2.85, 2.63)),

---

1 LOGN(val_1,val_2) = Lognormal probability distribution where val_1 is the mean and val_2 is the standard deviation.

2 GAMM(val_1,val_2) = Gamma probability distribution where val_1 is the beta value and val_2 is the alpha value.

3 EXPO(val_1) = Exponential probability distribution where val_1 is the mean.

- Time to remove and replace HP Turbine Module at Afloat AIMD level (LOGN(4.54, 4.05)),
- Time to remove and replace LP Turbine Module at Afloat AIMD level (GAMM(2.62, 1.81)),
- Time to remove and replace Afterburner Module at Afloat AIMD level (LOGN(3.19, 3.03)),
- Time to conduct preventative maintenance at Afloat AIMD level (LOGN(1.95, 2.11)).
- Time to repair Fan Module at Afloat AIMD level (-0.001 + EXPO(15.1)),
- Time to repair HP Compressor Module at Afloat AIMD level (-0.001 + GAMM(23.7, 0.978)),
- Time to repair Combustor Module at Afloat AIMD level (GAMM(5.67, 1.61)),
- Time to repair HP Turbine Module at Afloat AIMD level (-0.001 + GAMM(10.5, 1.29)),
- Time to repair LP Turbine Module at Afloat AIMD level (-0.001 + EXPO(10.7)),
- Time to repair Afterburner Module at Afloat AIMD level (-0.001 + GAMM(24.2, 0.846)).

In addition to the above list, the rates at which engines and modules are Beyond Capability of Maintenance (BCM) at the Afloat AIMD level of maintenance, and thus sent to a higher level for repair, were derived from the NALDA database and are listed in Table III.2 [Ref. 17]. The expression to compute these figures is

$$\frac{\sum(\text{BCM Codes 1 through 9}) \times 100}{\sum(\text{BCM Codes 1 through 9}) + \sum \text{Action Code B} + \sum \text{Action Code 2}}.$$

The BCM figures are used in the model to help direct flow of engines and modules at the flow points where whether to "BCM" (used as a verb to mean "send to a higher level of repair") the unit or not is decided.

After it is determined that an engine needs to be broken down for modular repair, the MTBF data from Table II.1 in is used to simulate the frequency of repair for each engine and module. Assuming an average of 300 flight hours per year per aircraft, the engine MTBF data was used to determine the interarrival time for each failed engine using the mathematical relationships

$$MTBF = \frac{1}{\lambda} \Leftrightarrow \lambda = \frac{1}{MTBF},$$

where λ represents the failure rate [Ref. 7: p. 30]. For the F404-GE-400 engine with a MTBF of 383.5 hours, the failure rate per hour is

$$\lambda = \frac{1}{383.5 \text{ hours}} = \frac{0.0026 \text{ failures}}{\text{hour}}.$$

The number of engine failures per year is solved from the relationship

$$\lambda = \frac{\text{number of engine failures}}{\text{total mission time}} \Leftrightarrow \text{number of engine failures} = \lambda \times \text{total mission time}$$

$$\Rightarrow \text{number of engine failures} = \frac{0.0026 \text{ failures}}{\text{hour}} \times \frac{300 \text{ hours}}{\text{year}} = \frac{0.7824 \text{ engine failures}}{\text{year}}.$$

The number of engine failures on the carrier per month is computed as

$$\frac{0.7824 \text{ engine failures}}{\text{year}} \times \frac{24 \text{ aircraft}}{\text{carrier}} \times \frac{2 \text{ engines}}{\text{aircraft}} \times \frac{1 \text{ year}}{12 \text{ months}} = \frac{3.129 \text{ engine failures}}{\text{month}}.$$

Or described in words, there are on average 3.129 engine failures onboard the aircraft carrier per month. Inverting this failure rate (for units cancellation purposes) and multiplying it by squadron operating hours per month yields the interarrival time that is used in the simulation model,

$$\frac{720\text{ hours}}{\text{month}} \times \frac{\text{month}}{3.129\text{ engine failures}} = \frac{230.1\text{ hours}}{\text{engine failure}}.$$

Again, in words, this means that during a deployment, an engine fails on average every 230.1 hours, or one in every 9.6 days.

Engine module failure rates are similarly computed from the MTBF data in Table II.2. However, instead of computing an interarrival time, the frequency of module failures is represented as a percentage of engine failures. This is computed by dividing the monthly module failure rate by the monthly engine failure rate (3.129). The results of these computations are listed in Table III.3. Since more than one module may fail per single engine failure, the sum of the percentages is more than "100%."

Unit	BCM Rate (%)
Engine	5.83
Fan Module	8.19
High Pressure Compressor	9.32
Combustor Module	6.02
High Pressure Turbine Module	7.93
Low Pressure Turbine Module	13.49
Afterburner Module	10.06

Table III.2. Beyond Capability of Maintenance (BCM) Rates.

Unit	Percentage
Fan Module	56.43
High Pressure Compressor	55.07
Combustor Module	49.84
High Pressure Turbine Module	55.39
Low Pressure Turbine Module	59.79
Afterburner Module	74.38

Table III.3. Module Failures as a Percentage of Engine Failures.

3. Independent Input Determinants

A design of experiment with two factors was chosen for the simulation of the number of engine modules in each module rotable pool. This is a form of a factorial experiment, or simulation, where all levels of a given factor (number of modules in the pool) are combined with all levels of every other factor in the simulation model [Ref. 18:p. 78]. In other words, the model is a simulation of n factors where each factor is at just two levels [Ref. 18:p. 95]. This is annotated as a 2^n Design of Experiment. In this model, two rotable pool inventory levels are considered for each of the six modules, so $n = 6$. Thus, a 2 X 6 factorial simulation would require 2^6, or 64, different simulation input combinations. This set, or table, of values for each factor is called the Simulation Plan, and is found in Appendix A.

The two values used for each factor, or module, are one and five. These numbers were chosen because the large difference between them ensures that any change in a module inventory level will be seen in the simulation model output. If too small a spread were used, the results would not be statistically significant and no conclusion could be

reached. These numbers were also chosen because although space constraints are a consideration, these levels are not beyond the realm of possibility for module inventories onboard an aircraft carrier.

E. SIMULATION MODEL DESCRIPTION

The actual simulation model is organized in three sections that correspond to Figures 2.2, 2.3 and 2.4. The purpose of this arrangement is for graphical reasons only to aid in the programming process and for clearer viewing of the simulation model design. Appendix B shows the simulation model as it appears on the computer screen in Arena. A static view of the simulation model animation is also provided in Appendix B.

The Squadron Engine Repair section simulates the arrival of an inoperable engine, based upon an exponential distribution with a mean of 230 hours, and further simulates the inspection process and potential repair process. If the engine is not repairable at this level, the model simulates engine removal from the aircraft. Engines that have been repaired and since returned to the Squadron level are simulated installed back into aircraft and the clock is reset for another engine failure based upon the interarrival time.

The AIMD Engine and Module Repair section of the model simulates the Maintenance Engineering Inspection, possible AIMD level engine repair and the possible routing of engines to a Shore AIMD or Depot for repair. Engines that are not repairable at this level, or are not sent to Shore AIMD or Depot, are sent to individual Afloat AIMD module repair shops that make up the third and last level of the simulation model.

The layout and Arena simulation modules for each module repair section are identical. Times for removal and replacement of a module, probabilities of needing repair, which are from Table III.3, and module repair times are unique for each module. As discussed in the assumptions above, modules that are not in need of repair experience a 50% chance of receiving preventative maintenance.

The next chapter provides the results of actual simulation runs, and from that data develops the metamodel itself. It discusses how the data is analyzed and exactly from where each term of the metamodel equation comes.

IV. METAMODEL DEVELOPMENT

A. SIMULATION RESULTS

In this chapter, we will describe the simulation's metamodel. Using Microsoft® Excel 97 spreadsheet software, a regression analysis was conducted on the simulation model A_O output as listed in the Simulation Plan (Appendix A). From that analysis, the metamodel is defined as

$$A_o = 0.8777 + 0.00060X_{Fan} + 0.00157X_{HPC} + 0.00066X_{HPT} + 0.00037X_{LPT} + 0.00154X_{AB},$$

where X_i annotates the number of modules in a module's initial rotable pool inventory, and i represents the term's module as listed below.

Fan = Fan Module
HPC = High Pressure Compressor Module
HPT = High Pressure Turbine Module
LPT = Low Pressure Turbine Module
AB = Afterburner Module.

The regression analysis statistics provide the coefficients for the module variables in the metamodel equation, as well as the y-intercept of 0.88 (rounded from 0.877703). The coefficient values represent the increase in A_O for every increase in that module's rotable pool initial stock. For example, for every additional High Pressure Compressor added to the initial stock, Squadron A_O increases by 0.16% (coefficient value is 0.001570). The regression statistics from analyzing the simulation results are listed in Appendix C.

The regression analysis also explains the absence of the Combustor Module as a term in the metamodel. This deficit occurs because the Combustor Module, in relation to the other modules, does not significantly contribute to increasing A_O as a function of the metamodel. Since the 95% confidence interval for the Combustor Module coefficient includes the value "0," we drop it out of the equation.

The metamodel, as presented above, can be used in determining optimum module inventory levels given a specific desired A_O, or for finding the highest expected A_O given preset module inventory levels without running simulations over again. The next section discusses the validity and correlations of the metamodel, and then the following sections explain in more detail its utility to planners and managers at the various levels of repair.

B. METAMODEL VALIDATION

1. Comparing Metamodel A_o with Simulation Model A_o

In order to validate the metamodel, the initial rotable pool inventory quantity for each module from the Simulation Plan was plugged into the metamodel and compared with the corresponding A_O data from the simulation runs. None of the differences between the simulation run A_O data and the metamodel A_O data exceeded 1% of the simulation run A_O data. This validates the metamodel in relation to the simulation model. Since the simulation model was in itself a detailed and accurate representation of the module repair cycle, it follows that the metamodel also represents it well.

2. Correlating Delay Time with Metamodel Coefficients

Another way of validating the metamodel is to look at what we expect the coefficients to be in relation to one another based upon our knowledge of MTBFs and repair times. It reasons that modules with a lower MTBF (i.e., fail more often) and modules with longer repair times would have more of an adverse affect on Squadron A_O than the other modules. Therefore providing more spare modules in the rotable pool would alleviate some of the delay caused by the lengthy repair of those modules, and A_O would be improved. Representing this higher marginal value, these modules would have a higher coefficient in the regression analysis statistics than the other modules.

Figure 4.1 shows the removal, repair and reinstall times (delay time) for each module. The High Pressure Compressor module exhibits the greatest time, and as expected also exhibits the greatest coefficient in the regression analysis, and hence in the metamodel. The Combustor Module, which had the smallest delay time and hence the least impact on delaying repair of an engine and hurting Squadron A_O, had the smallest coefficient. This correlation is strongly present throughout the coefficients and delay times for all of the modules, and further supports the validity of the metamodel. Figure 4.2 shows a graphical presentation of the coefficients and is presented below Figure 4.1 for easy visual comparison.

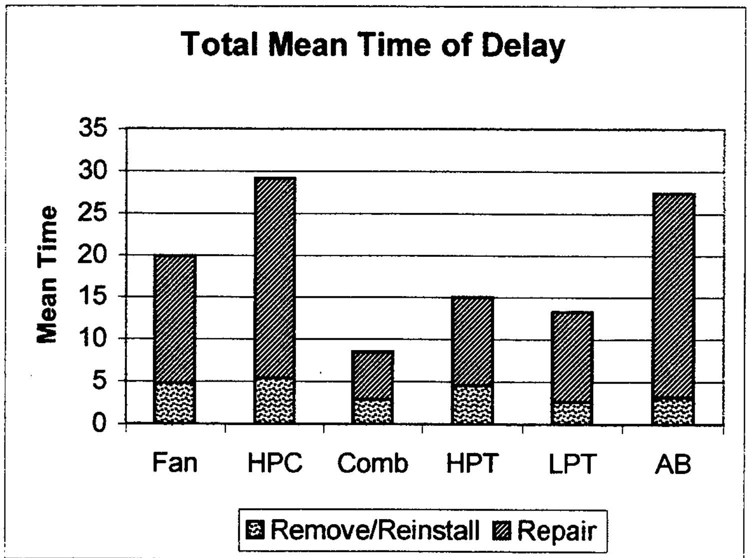


Figure 4.1. Module Total Mean Time of Delay.

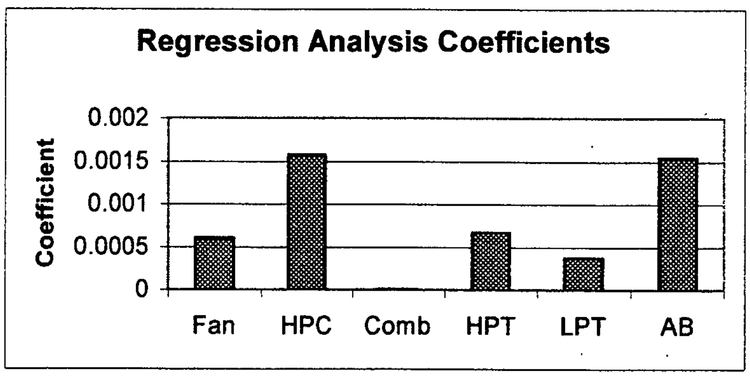


Figure 4.2. Metamodel Coefficients from the Regression Analysis.

3. Number of Iterations

Another consideration in collecting data for metamodel development is the choice of how many simulation iterations for each run. This has importance to ensure statistically sound data results. Since the run time difference between 20 simulation

iterations for each run and 50 is under one minute, the number of iterations chosen was 50. This ensured a large enough sample size, or number of observations, for each run to provide a mean A_O value that is statistically sound. After running the simulation model through 50 iterations for each of the 64 simulation runs, as described in Section D.3 of Chapter III, mean A_O data was collected for each run. This data is shown in the right column in Appendix A, the Simulation Plan and Results. The next section describes the meaning of the results.

C. RELATIONSHIPS BETWEEN FACTORS AND COST

The inventory mixes presented below represent the best values with the highest metamodel A_O's because they reflect each module's marginal contribution to A_O, as defined in the metamodel coefficients. This represents the greatest value of the metamodel. It provides tangible figures that show tradeoffs and consequences of making different inventory decisions. The paragraphs that follow in this section explain how.

A relationship between the metamodel and cost is easily established. But first, for comparison purposes, a baseline or total cost constraint must be found. The cost constraint equals the funds currently necessary to outfit a deploying aircraft carrier with established module allowances. The cost for such an undertaking is tied to the repair costs of the F404 engine and modules, since purchases of new engines and modules ended several years ago. A total cost constraint is found by multiplying the repair costs of each module (provided by Navy Inventory Control Point, Philadelphia) by the number

of modules allowed, and summing the products [Ref. 5]. Table IV.1 provides the results of this computation that is used as a baseline total cost for analysis purposes.

Module	**Allowance**	**Repair Cost**	**Total Cost ($)**
Fan	3	125,169	375,507
HP Compressor	2	67,411	134,822
Combustor	2	36,778	73,556
HP Turbine	3	59,507	178,521
LP Turbine	2	48,107	96,214
Afterburner	3	87,696	263,088
Grand Total Cost			1,121,708

Table IV.1. Total Cost Constraint Computation.

To study the relationships between total costs associated with a particular inventory mix and desired A_O values, a table was constructed that contains all inventory combinations and their corresponding metamodel A_O values. For each combination of module inventories, a total cost was computed using the individual module repair costs in Table IV.1. The inventory combinations, or mixes, varied from one each to five each for all of the six modules. Covering every combination, the table contains all 15,625 possible inventory mixes. The baseline for analysis of this table is established using the current module inventory allowances as listed in Table IV.1, and is shown as Scenario 1 in Table IV.2.

Scenerio	Metamodel A_o	Module						Net Savings
		Fan	HPC	Cmb	HPT	LPT	AB	
1	0.890	3	2	2	3	2	3	0
2	0.896	1	5	1	2	1	5	$17,105
3	0.895	1	5	1	1	1	5	$76,612
4	0.894	1	5	1	1	2	4	$116,201
5	0.893	1	5	1	1	1	4	$164,308
6	0.892	1	5	1	1	1	3	$252,004
7	0.891	1	5	1	1	2	2	$291,593
8	0.890	1	5	1	1	1	2	$339,700
9	0.889	1	5	1	1	1	1	$427,396
10	0.888	1	4	1	1	2	1	$446,700

Table IV.2. Module Inventories with Cost Savings at Different Metamodel A_O's.

Various searches were conducted on the table to compare metamodel A_O's and total costs for different inventory mixes. The table was searched for inventory mixes that have a metamodel A_O greater than the baseline's, and with a cost equal to or less than the baseline's (Scenario 1 in Table IV.2). The mix with the highest A_O, that also has a total cost equal to or less than the baseline, has a metamodel A_O of 0.896, as shown by Scenario 2 in Table IV.2. The table was then searched to find the least expensive inventory mix for each metamodel A_O between 0.888 and 0.896, incremented by 0.001. These results are listed in Table IV.2 as Scenarios 2 through 10.

The savings shown in Table IV.2 represent the difference between current total cost to outfit a deploying carrier and the new lower total cost of outfitting the carrier using the metamodel to determine sparing levels. For example, looking at Scenario 4 in Table IV.2, a squadron A_O of 0.894 is possible with one Fan, Combustor and High Pressure Turbine Modules, two Low Pressure Turbine Modules, four Afterburner

Modules, and five High Pressure Compressor Modules, all at a total cost $116,201 less than the baseline of $1,121,708.

Analyzing the changes in module quantities in Scenarios 2 through 10, and from the baseline, Scenario 1, reveals a clear pattern that is consistent with known maintenance delay times as discussed in the preceding section. The metamodel recommends stocking more of the modules that require the longest repair times, and fewer of the ones that require the least time. Both the High Pressure Compressor (HPC) and Afterburner Modules are recommended to have higher inventories, and they have the two highest repair times. The metamodel results recommend that the remaining four modules have fewer in their inventory, and correspondingly, they have the lowest repair times. The rate at which the metamodel recommended inventories drop also corresponds to the delay times, as can be seen by the high HPC Module recommended quantities in all scenarios. Since the HPC Module has the longest repair time, the metamodel consistently recommends that it have the greatest inventory, and waits until all the other modules' inventory levels are the minimum (one) before decrementing the HPC Module inventory.

Another revealing aspect of potential savings from implementing the metamodel recommendations, as seen in Table IV.2, is the difference between the baseline, Scenario 1, and Scenario 8. Both have the same metamodel A_O, yet Scenario 8 offers a saving of $339,700 with 4 fewer modules overall. The reasonableness of this saving, answers to the research questions posed by this thesis, and conclusions that can be made from Table IV.2 are the topics discussed in the next chapter.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Critical Factor Relationships

When considering rotable spare inventories of F404 engine modules, the critical factors in the module repair cycle during an aircraft carrier deployment are the number of all F404 engine modules in the initial rotable pool stock, with the exception of the Combustor Module. Increasing the number of Combustor Modules does not significantly affect Squadron Operational Availability (A_O), and adding additional modules of any other type does. The relationship between these factors is represented in the metamodel

$$A_o = 0.8777 + 0.00060X_{Fan} + 0.00157X_{HPC} + 0.00066X_{HPT} + 0.00037X_{LPT} + 0.00154X_{AB},$$

where X_i annotates the number of modules in a module's initial rotable pool inventory, and i represents the term's module as listed below.

Fan = Fan Module
HPC = High Pressure Compressor Module
HPT = High Pressure Turbine Module
LPT = Low Pressure Turbine Module
AB = Afterburner Module.

The ranking of modules by their marginal addition to A_O is possible by looking at their coefficients as expressed in the metamodel. The coefficients are also provided in the Table V.1. The greatest marginal contributor, the High Pressure Compressor Module,

adds 0.16% to Squadron A_O for every additional module stocked in the initial rotable pool inventory.

Module	Metamodel Coefficient, or Marginal A_o (%)
High Pressure Compressor	0.1570312
Afterburner	0.1539062
High Pressure Turbine	0.0664062
Fan	0.0601562
Low Pressure Turbine	0.0367187

Table V.1. Marginal Contribution to A_O by Module.

Using the metamodel to maximize A_O without increasing costs, the table introduced in Chapter IV that contains all 15,625 possible combinations of module inventories and corresponding metamodel A_O's was used to find the mix of modules that yields the highest A_O, while costing the same or less than the baseline inventory. However, another step is required to evaluate which mix is the best and that is looking at these mixes in the simulation model as well. The best cost inventory mixes listed in Table IV.2 were input into the simulation model and these results are added to Table IV.2 and are shown in Table V.2 below.

Three inventory mixes, Scenarios 4, 6 and 7, stand out as better solutions than the baseline when comparing metamodel and simulation A_O's to cost. All three have metamodel A_O's higher than the baseline's metamodel Ao. All three have 95% confidence intervals for their simulation A_O's that overlap. In other words, since their

confidence intervals overlap, neither is statistically different from the other. A list of the 95% confidence intervals for all scenarios in Table V.2 are provided in Appendix D. Of the three, Scenario 7 provides the greatest saving over the baseline of $291,593. This saving represents the lower cost of outfitting one aircraft carrier with two F/A-18 squadrons for one deployment. Spreading this saving over a fleet of carriers and it grows to millions of dollars saved in avoided inventory outfitting costs each year.

Scenario	**Meta-model A_o**	**Module**						**Net Savings**	**Simulation A_o**
		Fan	**HPC**	**Cmb**	**HPT**	**LPT**	**AB**		
1	0.890	3	2	2	3	2	3	0	0.903
2	0.896	1	5	1	2	1	5	$17,105	0.896
3	0.895	1	5	1	1	1	5	$76,612	0.895
4	0.894	1	5	1	1	2	4	$116,201	0.900
5	0.893	1	5	1	1	1	4	$164,308	0.889
6	0.892	1	5	1	1	1	3	$252,004	0.898
7	0.891	1	5	1	1	2	2	$291,593	0.898
8	0.890	1	5	1	1	1	2	$339,700	0.888
9	0.889	1	5	1	1	1	1	$427,396	0.887
10	0.888	1	4	1	1	2	1	$446,700	0.892

Table V.2. Module Inventories with Metamodel A_O's, Cost Savings and Simulated A_O's.

2. Practical Interpretation of Thesis

The metamodel developed from the simulation model is useful in determining F404 module inventory levels. The relationships between the critical factors are clearly shown in the metamodel and the module coefficients. The metamodel shows that by changing the mix of initial rotable pool F404 module inventories, squadron A_O is affected and can be maximized given cost or inventory constraints. The metamodel also shows

that significant (multi-million $) savings can be realized by following its inventory change recommendations. The metamodel is a simple mathematical equation that can be used by anyone for any of the purposes discussed in this thesis.

Additionally, the metamodel results can be generalized to sparring level policies for a wide family of weapon systems. Processes, that cause delay in restoring systems, for components and parts that have known histories of high failure rates, long repair turnaround times, and high costs, are prime candidates for simulation analysis. The benefits are greater A_O levels at lower inventory costs.

In summary, the metamodel derived in this thesis provides a simple process by which engine maintenance personnel may compute spare module inventory levels. It also provides important insight into which modules are significant in the repair process. Consequently, it provides valuable guidance for beneficial inventory changes, as are shown in the next section.

B. RECOMMENDATIONS

1. Module Rotable Pool Allowances

Based upon the metamodel that we derived in this thesis, we recommend that the initial inventory quantities for the F404-GE-400 engine modules onboard aircraft carriers be changed to those shown in Table V.3. The difference in total cost from the NAVAIR allowances is a saving of $291,593 for one deployment. Multiply this saving by four (the minimum number of aircraft carrier deployments per year) and the total Navy-wide annual savings are over $1.16 million.

Since the basis of the above recommendation is cost savings while not affecting A_O, another valid approach is maximizing A_O without increasing costs. This results in a recommended mix as listed in Table V.4. This mix is in fact the only one of 2,464 combinations of module inventories in the table with a metamodel A_O of .896. It is interesting to note however, that the simulated A_O of the recommended inventory mix in Table V.3 (Scenario 2 in Table V.2) is greater than the simulated A_O of the recommended inventory mix in Table V.4 (Scenario 7 in Table V.2).

Module	**Allowance Quantity**	**New Quantity**	**Total Cost ($) Change**
Fan	3	1	-250,338
HP Compressor	2	5	+202,233
Combustor	2	1	-36,778
HP Turbine	3	1	-119,014
LP Turbine	2	2	—
Afterburner	3	2	-87,696
Total Cost Savings with Changes in Quantities			**-291,593**

Table V.3. Recommended New Module Allowances Based Upon Cost Savings.

Module	**Allowance Quantity**	**New Quantity**	**Total Cost ($) Change**
Fan	3	1	-250,338
HP Compressor	2	5	+202,233
Combustor	2	1	-36,778
HP Turbine	3	2	-59,507
LP Turbine	2	1	-48,107
Afterburner	3	5	+175,392
Total Cost Savings with Changes in Quantities			**-17,105**

Table V.4. Recommended New Module Allowances Based Upon A_O.

2. Updating the Metamodel

We further recommend that the simulation factors are updated once a year with current data and the metamodel recomputed in the same manner to determine shifts in significance among the modules. Inventory levels should be adjusted to reflect the changes, and Squadron A_O will always benefit.

3. Expanding Use of the Metamodel and Further Research Topics

Additionally, this concept of simulating repair cycles should be expanded to more high-dollar parts. There are significant inventory savings potential throughout the aviation depot level repairable systems. But more importantly, the classification of parts by their contribution to A_O is a new and worthwhile concept. By setting stocking levels based upon contribution to A_O, real improvements in readiness will be realized.

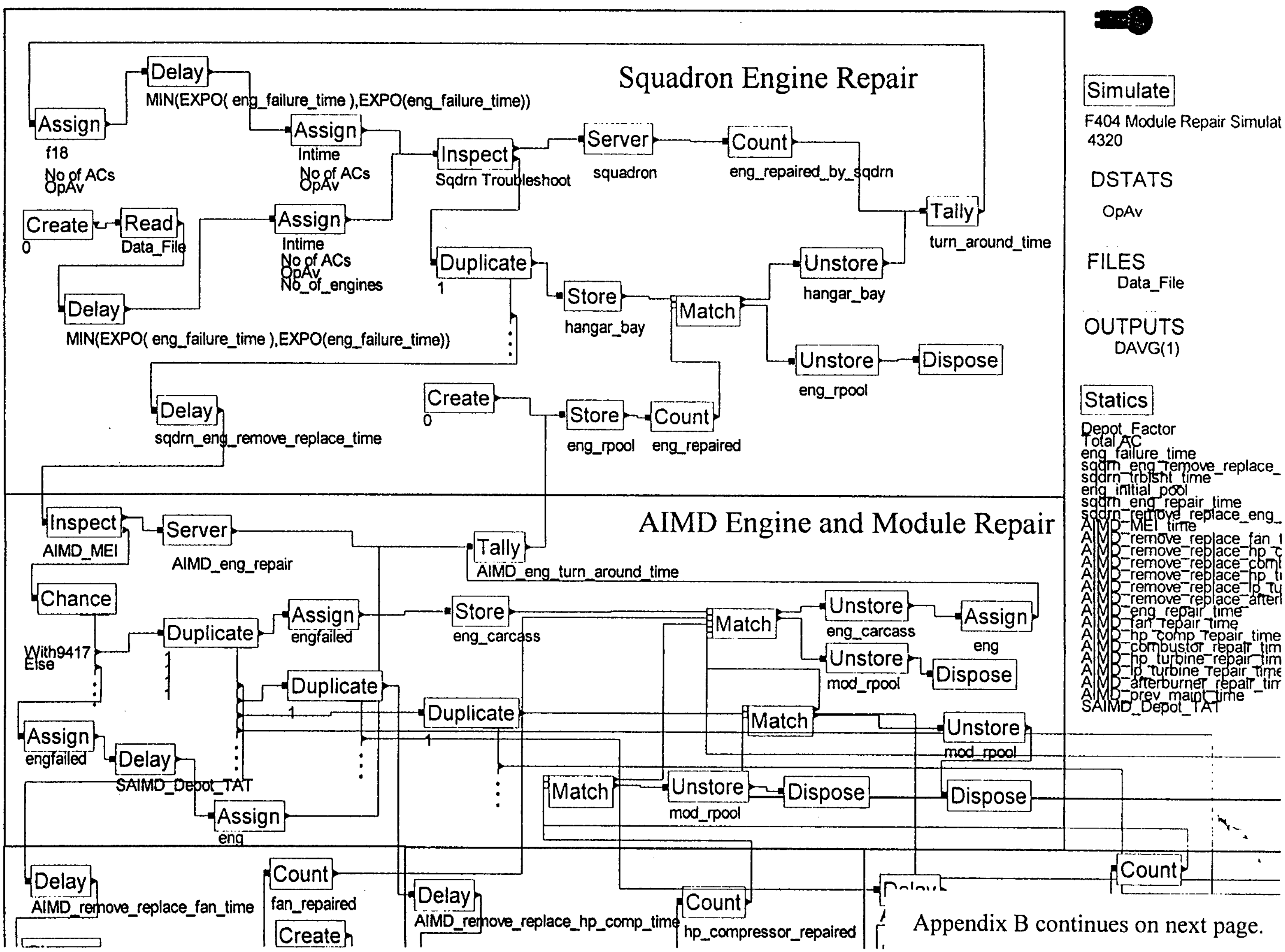
Another approach to determining inventory levels by using simulation modeling involves evaluating fill rates and their effect on readiness. For example, the simulation model developed in thesis could be modified so that delays in repair took into consideration awaiting piece part times. After fixing the module sparing levels, a Design of Experiment could be done with a high and low value for delay time due to awaiting piece parts. The results would show which parts affect Squadron A_O the most.

As readiness continues to grow in importance, and budgets continue to be cut, simulation modeling as a tool for inventory management becomes imperative, especially when considering the small investment in time and effort to produce such useful information.

APPENDIX A. SIMULATION PLAN AND RESULTS (50 REPLICATIONS FOR EACH RUN)

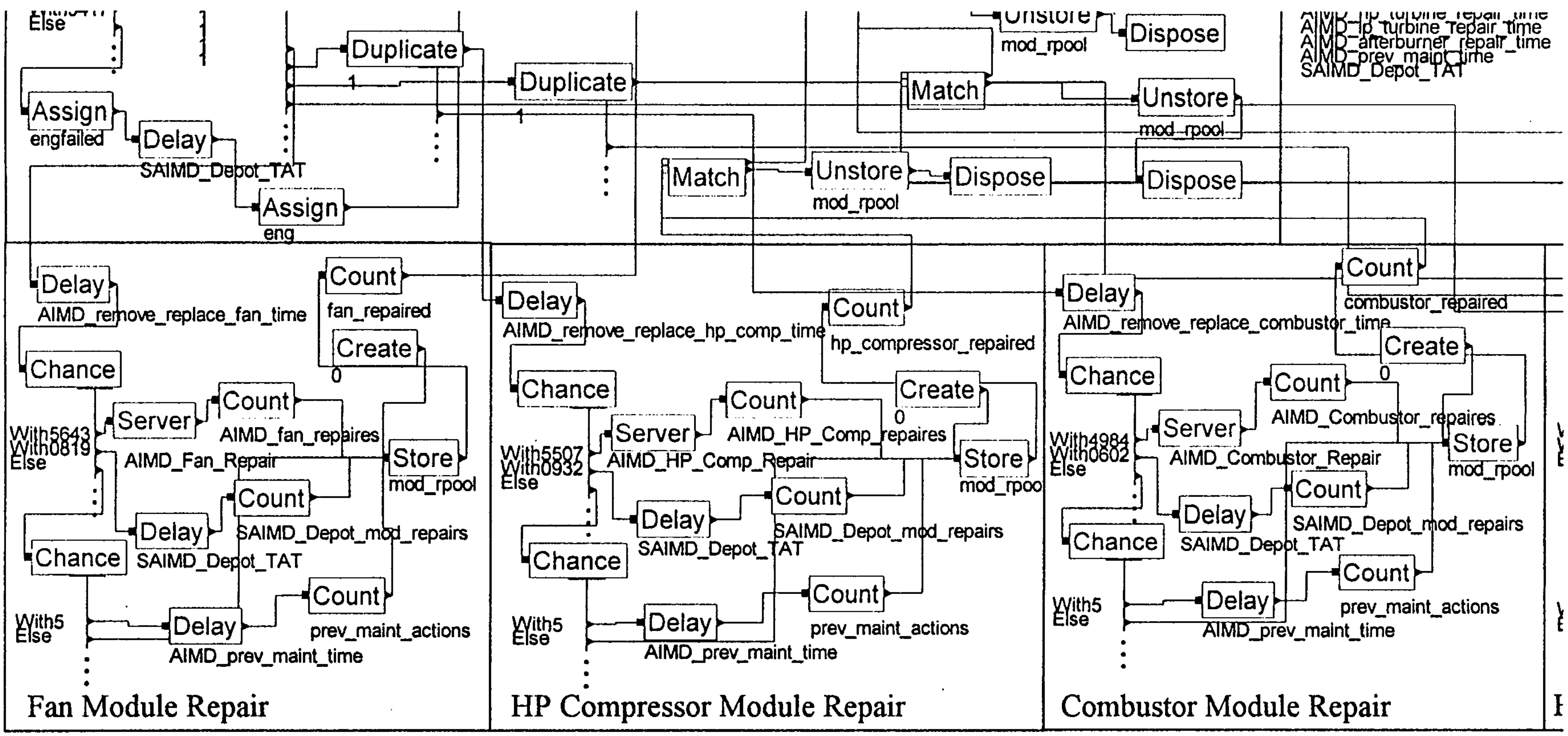
Simulation Run No.	Number of Modules: Fan	HP Comp	Combstr	HP Turb	LP Turb	AftrBrnr	AveOpAv
1	1	1	1	1	1	1	0.883
2	1	1	1	1	1	5	0.888
3	1	1	1	1	5	1	0.888
4	1	1	1	1	5	5	0.892
5	1	1	1	5	1	1	0.886
6	1	1	1	5	1	5	0.891
7	1	1	1	5	5	1	0.886
8	1	1	1	5	5	5	0.890
9	1	1	5	1	1	1	0.882
10	1	1	5	1	1	5	0.891
11	1	1	5	1	5	1	0.883
12	1	1	5	1	5	5	0.888
13	1	1	5	5	1	1	0.888
14	1	1	5	5	1	5	0.890
15	1	1	5	5	5	1	0.885
16	1	1	5	5	5	5	0.888
17	1	5	1	1	1	1	0.887
18	1	5	1	1	1	5	0.895
19	1	5	1	1	5	1	0.891
20	1	5	1	1	5	5	0.896
21	1	5	1	5	1	1	0.892
22	1	5	1	5	1	5	0.899
23	1	5	1	5	5	1	0.893
24	1	5	1	5	5	5	0.898
25	1	5	5	1	1	1	0.891
26	1	5	5	1	1	5	0.894
27	1	5	5	1	5	1	0.889
28	1	5	5	1	5	5	0.898
29	1	5	5	5	1	1	0.892
30	1	5	5	5	1	5	0.899
31	1	5	5	5	5	1	0.892
32	1	5	5	5	5	5	0.899
33	5	1	1	1	1	1	0.889
34	5	1	1	1	1	5	0.889
35	5	1	1	1	5	1	0.887
36	5	1	1	1	5	5	0.893
37	5	1	1	5	1	1	0.886
38	5	1	1	5	1	5	0.893
39	5	1	1	5	5	1	0.889
40	5	1	1	5	5	5	0.896
41	5	1	5	1	1	1	0.886
42	5	1	5	1	1	5	0.888
43	5	1	5	1	5	1	0.889
44	5	1	5	1	5	5	0.891
45	5	1	5	5	1	1	0.888
46	5	1	5	5	1	5	0.896
47	5	1	5	5	5	1	0.885
48	5	1	5	5	5	5	0.898
49	5	5	1	1	1	1	0.894
50	5	5	1	1	1	5	0.889
51	5	5	1	1	5	1	0.891
52	5	5	1	1	5	5	0.903
53	5	5	1	5	1	1	0.893
54	5	5	1	5	1	5	0.899
55	5	5	1	5	5	1	0.891
56	5	5	1	5	5	5	0.905
57	5	5	5	1	1	1	0.889
58	5	5	5	1	1	5	0.900
59	5	5	5	1	5	1	0.893
60	5	5	5	1	5	5	0.893
61	5	5	5	5	1	1	0.890
62	5	5	5	5	1	5	0.902
63	5	5	5	5	5	1	0.896
64	5	5	5	5	5	5	0.910

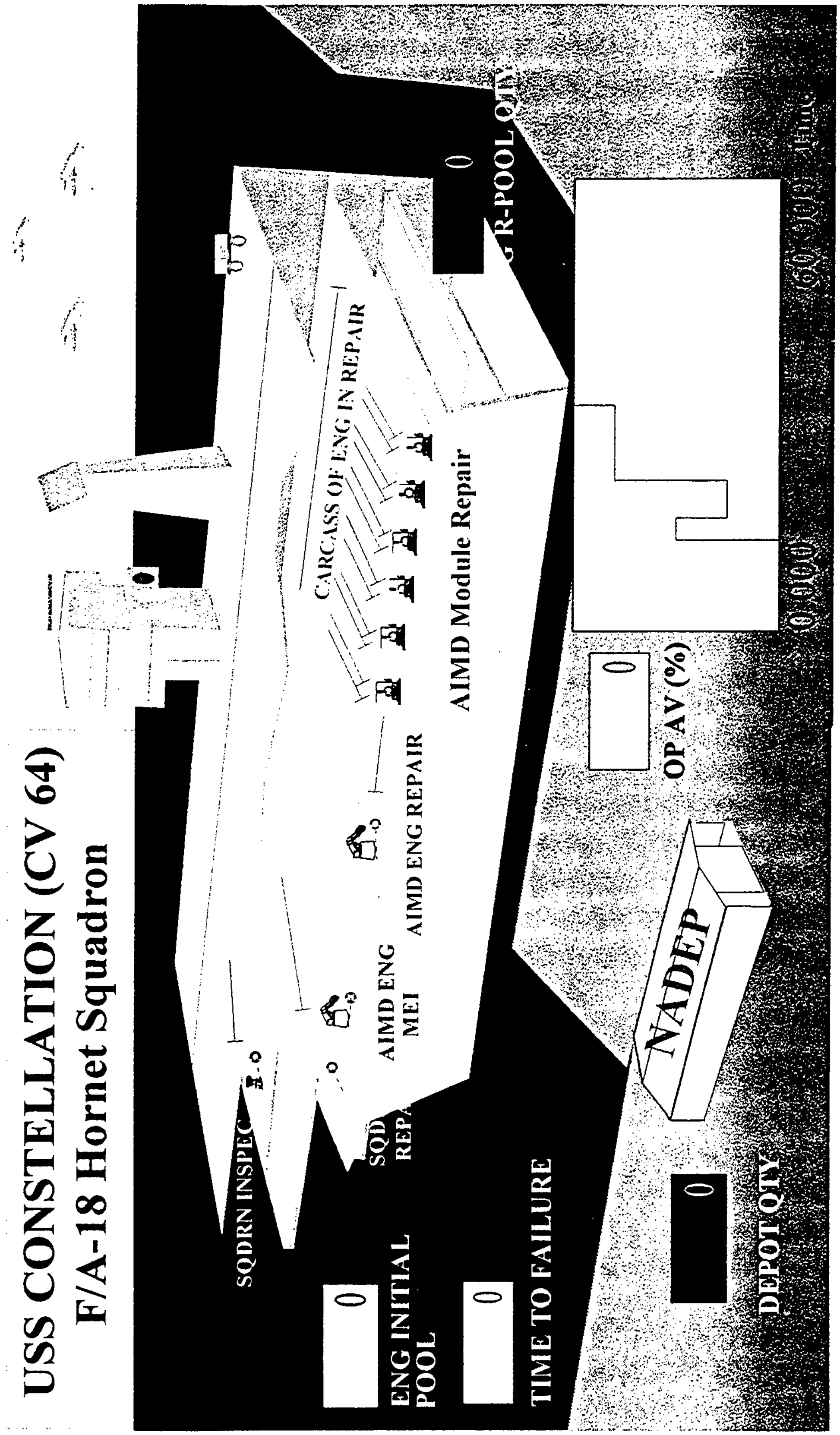
APPENDIX B. SIMULATION MODEL



Appendix B continues on next page.

Appendix B continued from previous page.





USS CONSTELLATION (CV 64)
F/A-18 Hornet Squadron
ENG INITIAL POOL
0
TIME TO FAILURE
0
SQDRN INSPEC
SQD REPA
AIMD ENG MEI
AIMD ENG REPAIR
CARCASS OF ENG IN REPAIR
AIMD Module Repair
0
R-POOL QTY
OP AV (%)
0
NADEP
DEPOT QTY
0

APPENDIX C. REGRESSION STATISTICS AND ANALYSIS

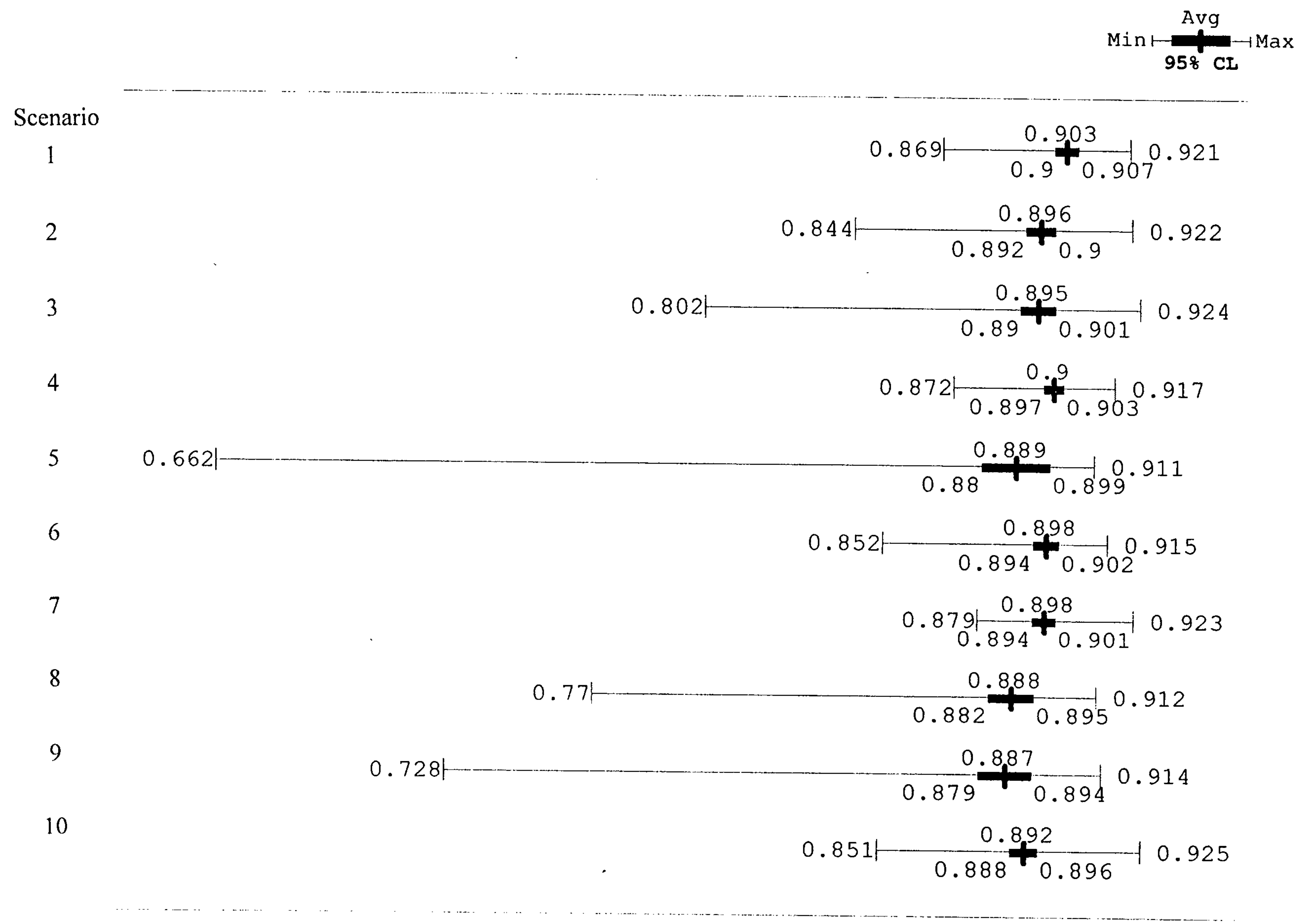
Multiple R	0.878012634
R Square	0.770906186
Adjusted R Square	0.746791048
Standard Error	0.002775648
Observations	64

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	6	0.001477719	0.000246286	31.96772816	1.57117E-16
Residual	57	0.000439141	7.70422E-06		
Total	63	0.001916859			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.877703125	0.001321169	664.3382383	1.5373E-112	0.875057528	0.880348722
Fan	0.000601562	0.000173478	3.467658797	0.001005855	0.000254179	0.000948946
HP Comp	0.001570312	0.000173478	9.051940497	1.27014E-12	0.001222929	0.001917696
Combstr	7.8125E-06	0.000173478	0.04503453	0.96423719	-0.000339571	0.000355196
HP Turb	0.000664062	0.000173478	3.827935036	0.000323524	0.000316679	0.001011446
LP Turb	0.000367187	0.000173478	2.116622902	0.038669734	1.98037E-05	0.000714571
AftrBrnr	0.001539062	0.000173478	8.871802377	2.50211E-12	0.001191679	0.001886446

APPENDIX D. 95% CONFIDENCE INTERVALS OF OPERATOINAL AVAILABILITY (SCENARIOS 1 THROUGH 10 FROM TABLE V.2)



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